Handbook for Operating a Spectra-Physics™ Quanta-Ray Pro-Series Nd-YAG laser and MOPO-SL (Master Oscillator Power Oscillator) Utilizing WinSpec™

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DISCLAIMER

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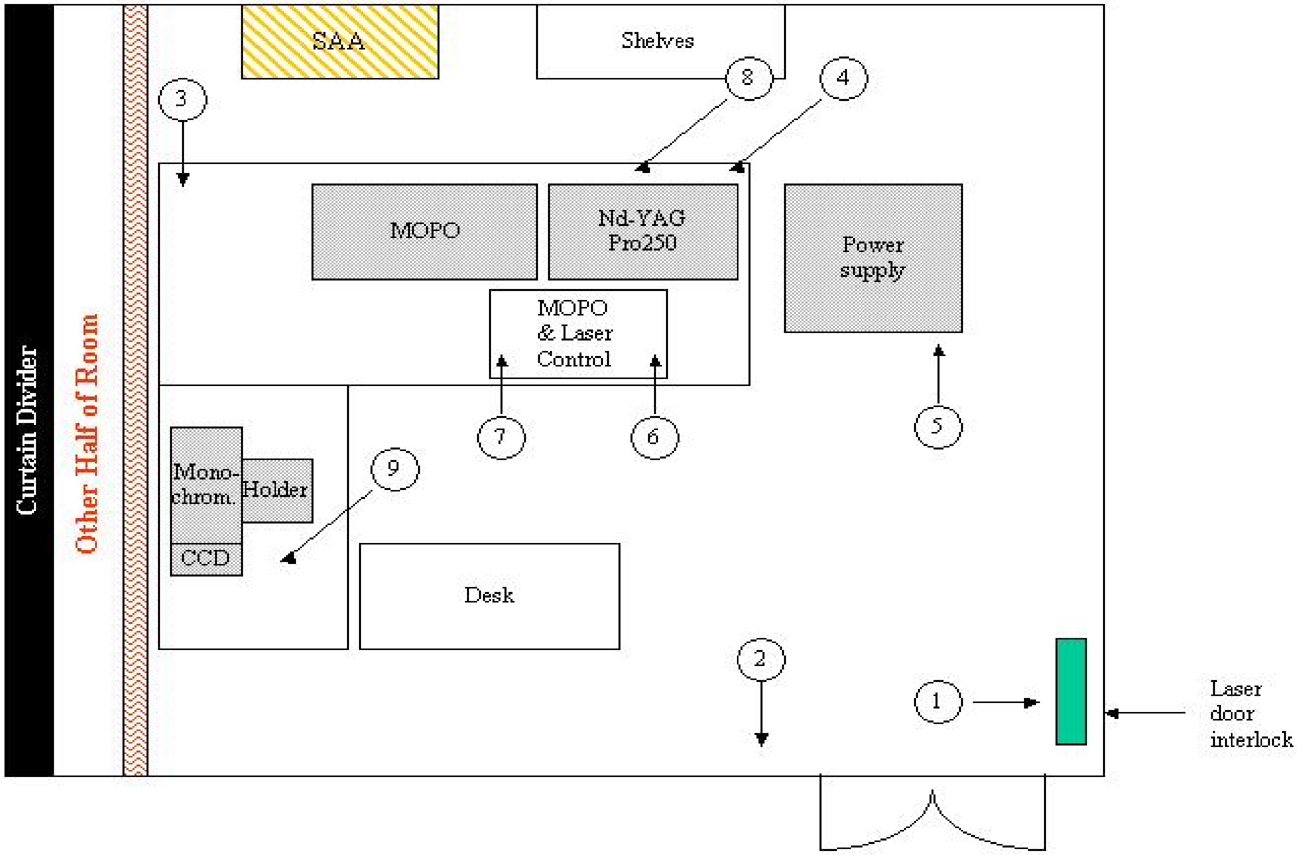
- **Map of layout of 70A-1169B**



Floor Plan: Above is a floor plan of the laser lab. Note that only western half of the room is shown.

- **Decide which wavelength is to be used. Refer to chart below on which units/crystals are needed.**

Wavelength	FDO	Crystal	Wavelength Type
220.0 – 272.0 nm	Yes	56 °	Signal
272.0 – 345.0 nm	Yes	36 °	Signal
345.1 – 365.9 nm	None	--------	---------
366.0 – 440.0 nm	Yes	36 °	Idler
420.0 – 700.0 nm	No	36 °	Signal
700.0 – 2200 nm	No	36 °	Idler

- **Decide if the Frequency Doubling Option (FDO) is to be used. If not, physically remove the FDO from the laser.**

Nd-YAG-laser:

1. **Switch door interlock "ON" by depressing the red "ON" button.** (See Floor Plan ① on pg. 1 and Figure 1)

Figure 1. Door Interlock Panel

2. **Open the nitrogen gas supply: blue valve and wheel on gauge (labeled GCR, DCR, Wex) at right side of the door.** (This is usually left open for convenience) (See Floor Plan ② on pg. 1 and Figure 2)

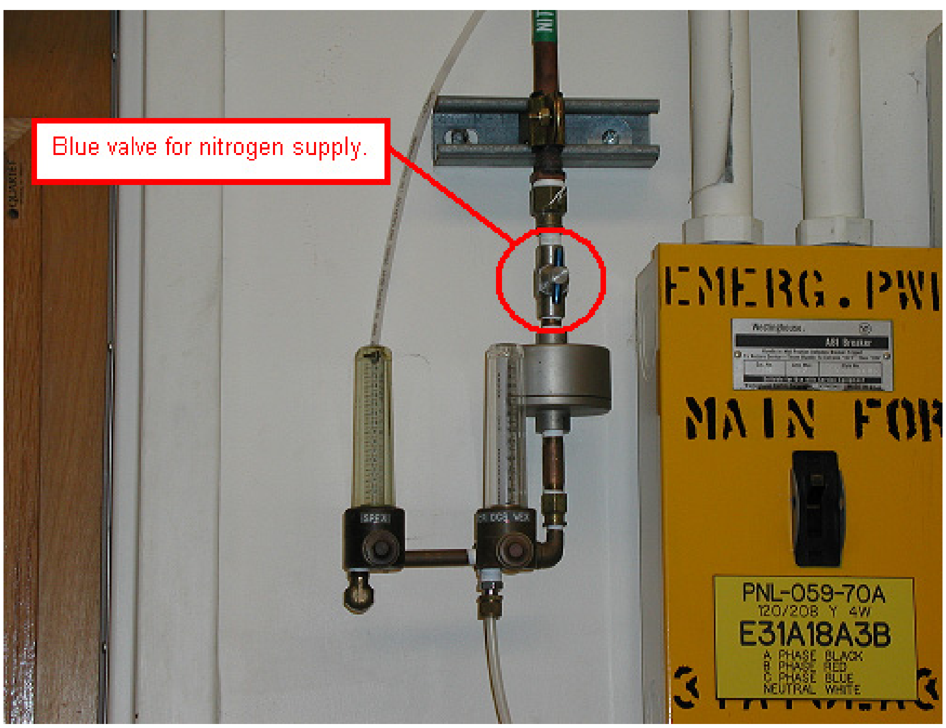


Figure 2: Location of blue valve for nitrogen supply valve. Usually, this valve is left open for convenience.

3. **Open the black valve at nitrogen distribution** (fixed to copper tubing for water inflow above backside of optical table). If valve is parallel to the ground, nitrogen valve is closed. If valve is perpendicular to the ground (pointed to "ON"), valve is on. (This is usually left open for convenience) (See Floor Plan ③ on pg. 1 and Figure 3)

4. **Open the yellow water valve under optical table (valve with pipe marked "IN") to a 45^{o}-60^{o} angle.** The water serves as a cooling mechanism. The outgoing valve shall be left open at all times. (See Floor Plan ③ on pg. 1 and Figure 3)

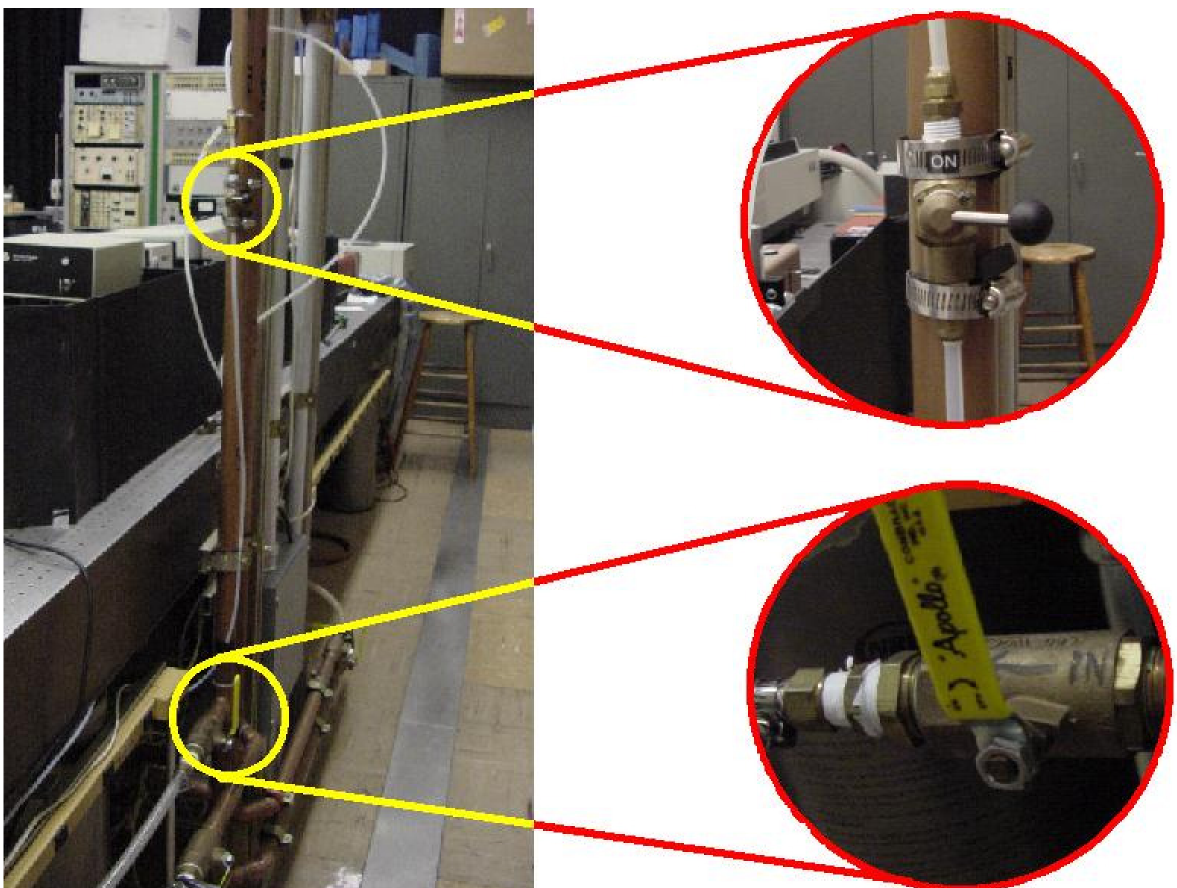


Figure 3: Left shows the relative positions of the nitrogen and water valves. Upper right shows what the nitrogen valve looks like in the "OFF" position". Lower right shows what the water valve looks like in the OFF position. Note that the valve in concern has an "IN" written on it. The "OUT" valve has been taped so that valve is opened at all times.

5. **Check the nitrogen flow at gauge on the right side of Nd-YAG laser and adjust to 0.4-0.6 scfh** (standard cubic feet per hour). (See Floor Plan ④ on pg. 1 and Figure 4)

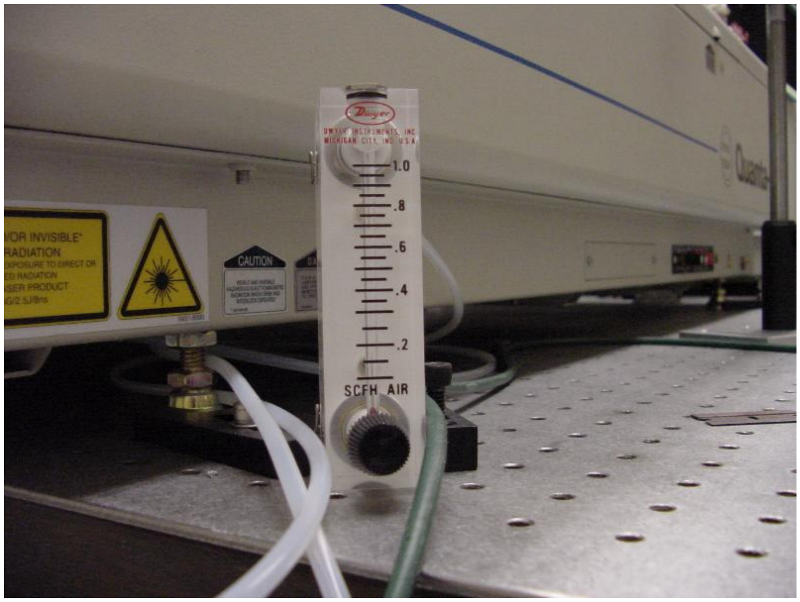


Figure 4: Picture of Nitrogen Distribution Meter.

6. **Turn the key on the laser power supply to ON.** The switch below the key should always be left on to warm the crystal. (See Floor Plan ⑤ on pg. 1 and Figure 5)

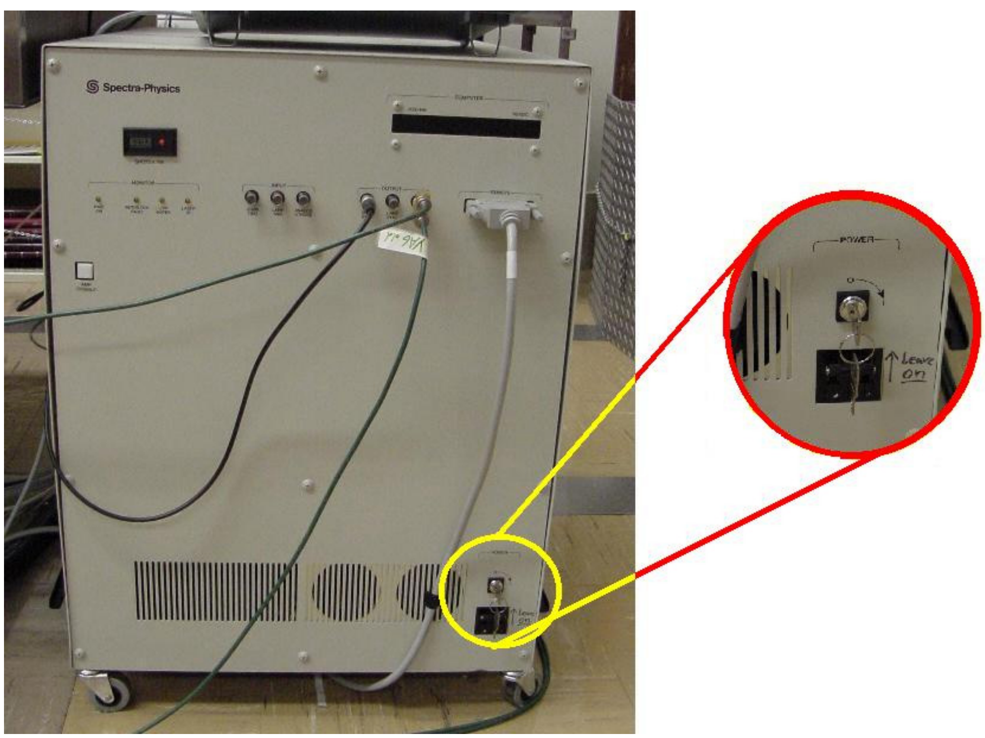


Figure 5: Picture of Power Supply and where the key is located. In the above picture, the key is in the OFF position.

7. **Turn on the Nd-YAG and MOPO controller (backside).** (See Floor Plan ⑥ on pg. 1 and Figure 6)

Figure 6: Top left shows the front of the Nd-YAG and MOPO. Top right shows the back of the Nd-YAG and MOPO controller where the ON/OFF switches are located.

8. **Press "POWER ON" (hold until beeps) in menu of Nd-YAG controller.** "SELF-TEST" will begin and laser will run in "Q-SWITCH OFF" mode. (See Floor Plan ⑦ on pg. 1 and Figure 7 and 8)

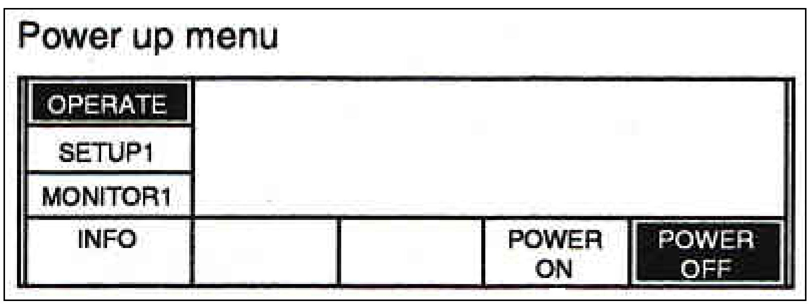


Figure 7: Starting menu when the Beamlock controller (i.e. Nd-YAG Controller) is turned on.

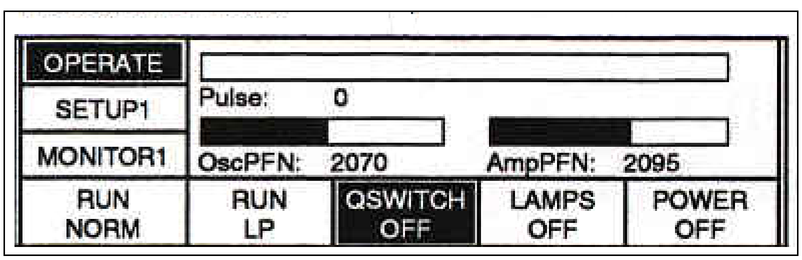


Figure 8: Menu that appears after pressing "POWER ON"

9. **Let the laser warm up for 10-15 min.** (See Floor Plan ⑦ on pg. 1)

10. **Press "RUN LP" (hold until beeps) in menu.** Long pulse mode will begin to run. **Let the laser warm up for 20-30 min.** (See Figure 9)

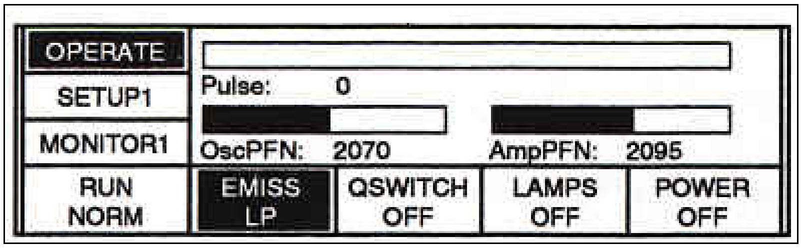


Figure 9: Menu after pressing "RUN LP"

11. **Press "RUN NORM" (hold until beeps) in menu.** Laser will ramp up oscillator and amplifier, BEAM LOK and D-LOK are checked. If everything is OK the laser will operate. "PULSE" should be around 1000 units (upper bar scale) under optimal conditions (new lamps). Expect the maximum "PULSE" to be between 880-1000 units. (See Figure 10)

Figure 10: Picture of a normally operating Nd-YAG Controller. Notice that the "PULSE" is 876, far below the optimum 1000 units.

12. **Let laser run for additional 10-15 min.** This is for warming up the FDO and MOPO crystals.

13. **Open the Harmonic Generator (HG) lid on the side of the Nd-YAG.** **Laser emission at 534 nm (UV-Visible) – eye protection !!!!** **Turn upper screw very careful (only a few μm) with the pulse reading in sight and optimize pulse.** **Then turn the lower screw and optimize.** This is to optimize the laser's FDO position so the maximum power leaving the Nd-YAG is achieved. Note: Lower screw is more sensitive than upper screw. There is a slight time delay from turning the screws and the pulse reading on the Beamlock Controller. (See Floor Plan ⑧ on pg. 1 and Figure 11)

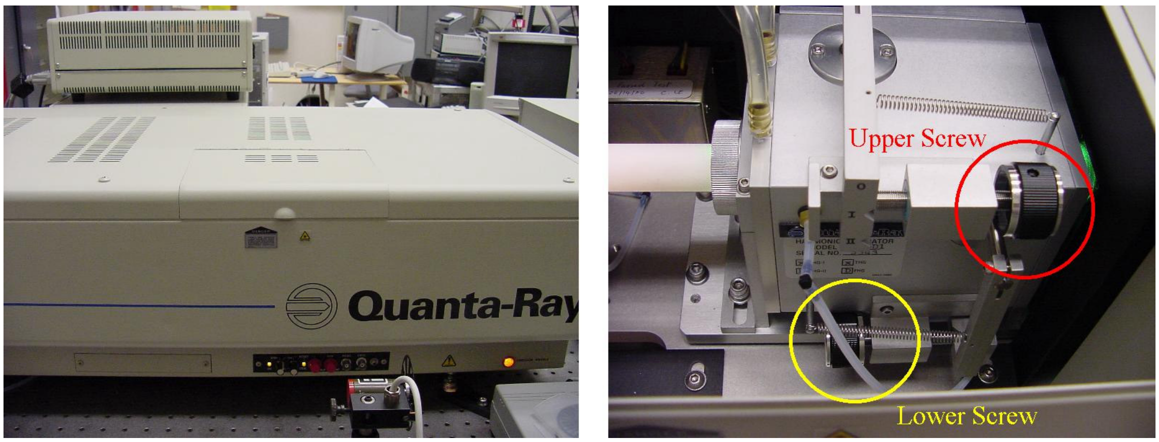


Figure 11: Left picture shows the location of the hatch containing the Harmonic Generator (HG). Right shows the location of the screws upon opening the hatch.

MOPO:

- From Page 1, decide if running with or without FDO. If the FDO needs to be used, place the prism unit inside the MOPO in the beam path (label: prism active). If the FDO is not to be used, physically remove the unit. (See Figure 12) Refer to the MOPO-SL manual for more instructions. When working on the prism, switch Nd-YAG to "Run LP", or better yet, "OFF"!!! Eye protection at 1068 nm!!

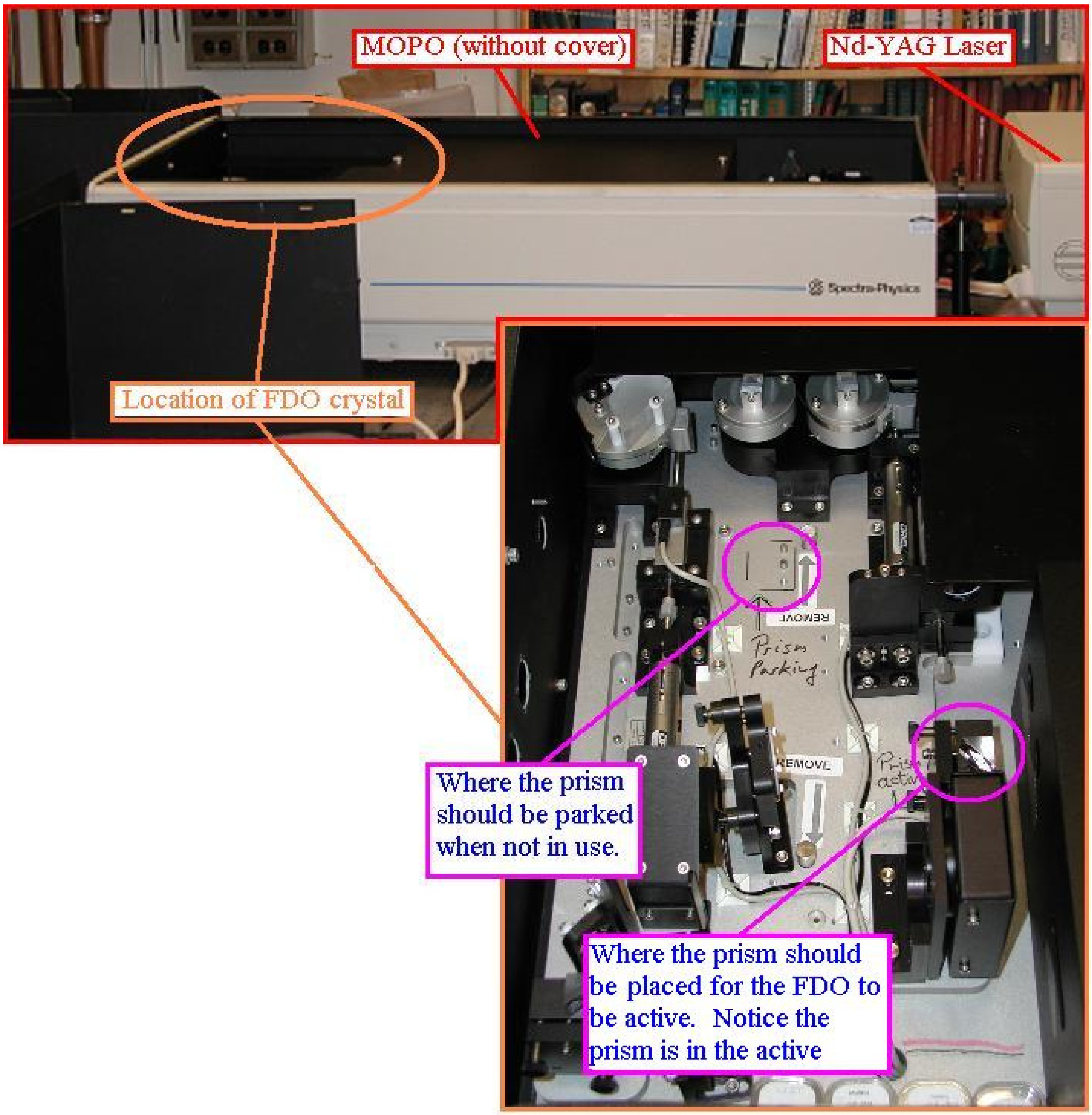


Figure 12: Shows location of prism that activates the FDO crystal. Note the two parking position of the prism.

With FDO at fixed wavelength

1. **Inside the MOPO, physically place the prism into the "Prism Active" position.** (See Figure 12) Note: It is best to have Nd-YAG laser off before removing the FDO unit. Otherwise, putting the laser under "RUN LP" should be sufficient as long as laser safety goggles are worn at 1068 nm.

2. **On the MOPO controller press "SCAN SETUP" button to "SETUP 1".** This menu enables you to choose the range in which the target wavelength falls.

3. **Choose a "START" and "END" wavelength below and above the target wavelength, respectively.** Input a range where the desired wavelength falls in between. To move the cursor, press either the "BEGIN" or END" button momentarily. Use the up/down buttons at far right to change the numbers. (See Figure 13).

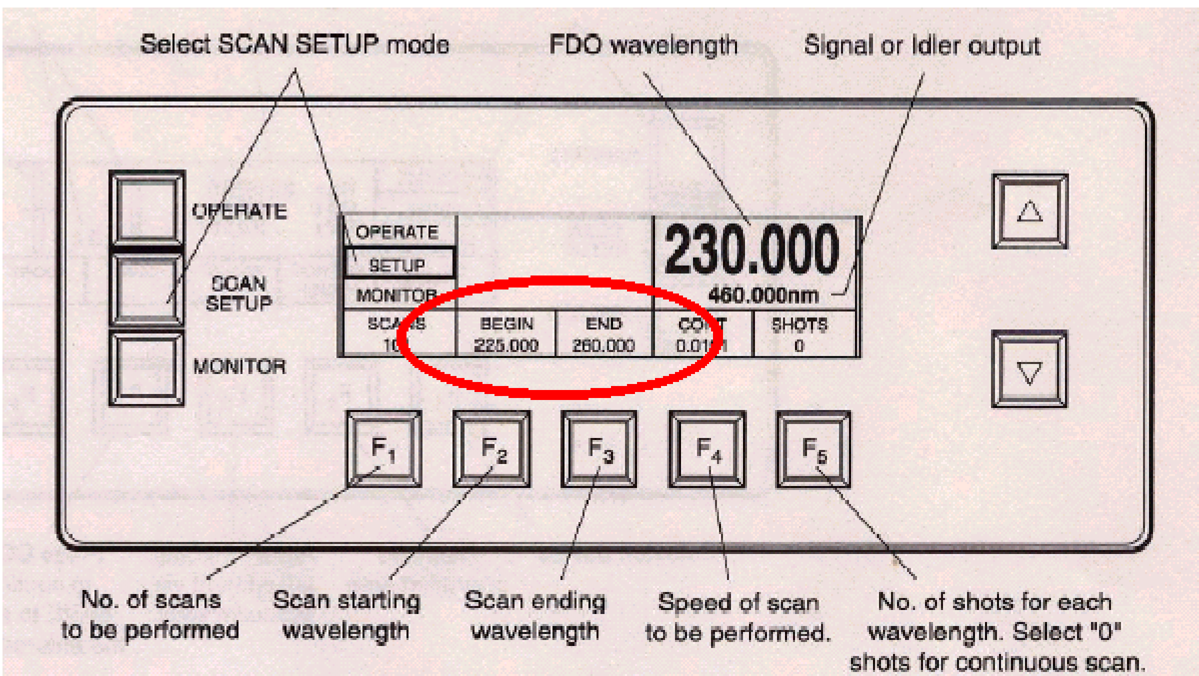


Figure 13: Menu that should appear on the MOPO controller after executing Step 2.

4. **Press "OPERATE" button to "OPERATE 1".** This menu allows you to set the target wavelength.

5. **Select wavelength with "GOTO" menu button.** Move the cursor by momentarily pressing the "GOTO" button. Use the up and down buttons at far right to change the numbers.

6. **Press and hold until beeps to set**.

7. **Press "SCAN SETUP" twice to "SETUP 2" menu.** This menu will allow you to maximize the power output of the MOPO at the target wavelength. See Step 8 for details. You also need to choose the device. (See Figure 14)

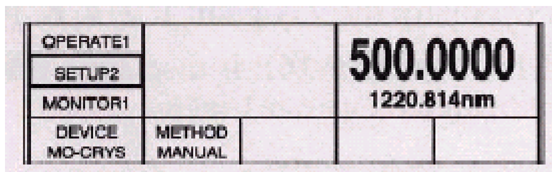


Figure 14: Menu that should appear on the MOPO controller after executing Step 5.

8. **Press "DEVICE MO-CRYS" and use the up/down keys until the "56°- CRYSTAL" (signal doubler) or "36°- CRYSTAL" (idler doubler) until beeps.** (See Figure 14) Refer to the chart on Pg. 1 if necessary.

9. **Select and press "METHOD MANUAL" again until beeps.** (Note: Selecting any other mode other than "METHOD MANUAL" will erase tables stored in MOPO controller).

10. **New menu appears. Output number (a representation of power) can be maximized with arrows up and down at right side of the MOPO controller.** This manual setting is temporary and is not saved.

11. **If change of wavelength is necessary, press "ABORT" momentarily to leave, returning settings to table value**.

No FDO: Signal or Idler at fixed wavelength

1. **Physically place the prism into the "Prism Park" position.** (See Figure 12) This is because the prism physically blocks the Signal regimes beam path.
   Note: It is best to have Nd-YAG laser off before removing the FDO unit. Otherwise, putting the laser under "RUN LP" should be sufficient as long as laser safety goggles are worn at 1068 nm.

2. **In the monitor menu, select "MOPO TRACK"**.

3. **Press the "OPERATE" button to "OPERATE 2" menu. Switch to either "MODE SIGNAL" or "MODE IDLER"** depending of frequency you want to look at (refer to table on pg.1).

4. **Choose a "START" and "END" wavelength below and above the target wavelength, respectively.** Input a range where the desired wavelength falls in between. To move the cursor, press either the "BEGIN" or END" button momentarily. Use the up/down buttons at far right to change the numbers.

5. **Press "OPERATE" button to "OPERATE 1".** This menu allows you to set the target wavelength.

6. **Select wavelength with "GOTO" menu button.** Move the cursor by momentarily pressing the "GOTO" button. Use the up and down buttons at far right to change the numbers. Press and hold until beeps to set.

7. **Press "SCAN SETUP" twice to "SETUP 2" menu.** This menu will allow you to maximize the power output of the MOPO at the target wavelength. See Step 8 for details. You also need to choose the device

8. **Press "MO-CRYSTAL " until beeps.**

9. **Select and press "METHOD MANUAL" again until beeps.** (Note: Selecting any other mode other than "METHOD MANUAL" will erase tables stored in MOPO controller).

10. **New menu appears. Output number (a representation of power) can be maximized with arrows up and down at right side of the MOPO controller.** This manual setting is temporary and is not saved.

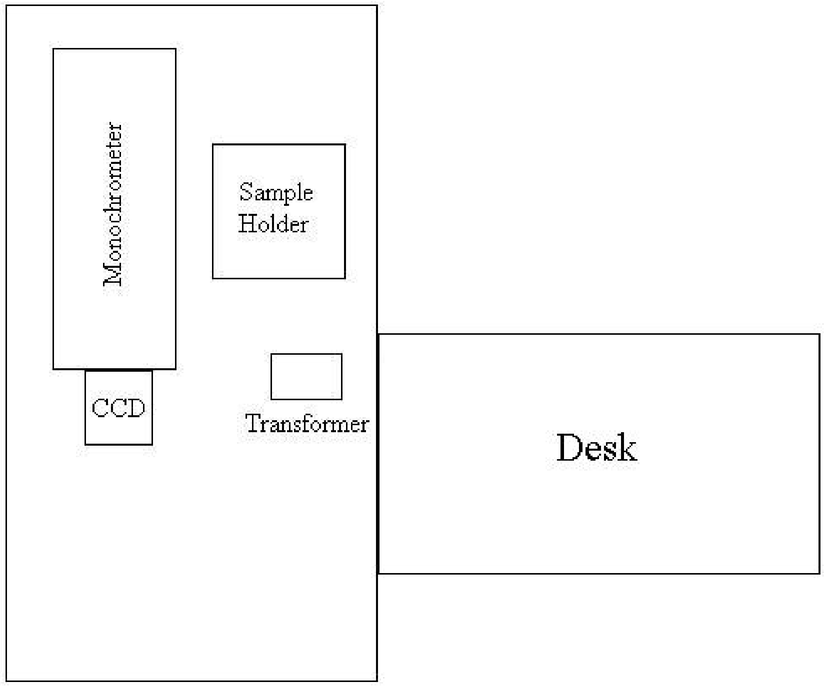
If change of wavelength is necessary, press "ABORT" momentarily to leave, returning settings to table value.

Notes on Operation

There is an inherent problem with the MOPO in that its energy fluctuates between laser shots and the maximum energy decreases over time. To correct this we have installed an energy meter. The energy meter is used to determine the exact amount of energy per laser shot. This especially useful if the laser is going to be used over longer periods of time when laser power is inconsistent.

Turning on the CCD Camera

Detector Floor Plan



- **Turn on following 3 devices in no particular order**
  - **Turn on the transformer located about 50 cm left of the black sample holder box. (See Detector Floor Plan and Figure 15)**

Figure 15: Picture of the transformer. Currently in the "ON" position

- **Turn on the CCD, located behind the Multi-Function Optical Meter. (See Detector Floor Plan and Figure 16)**

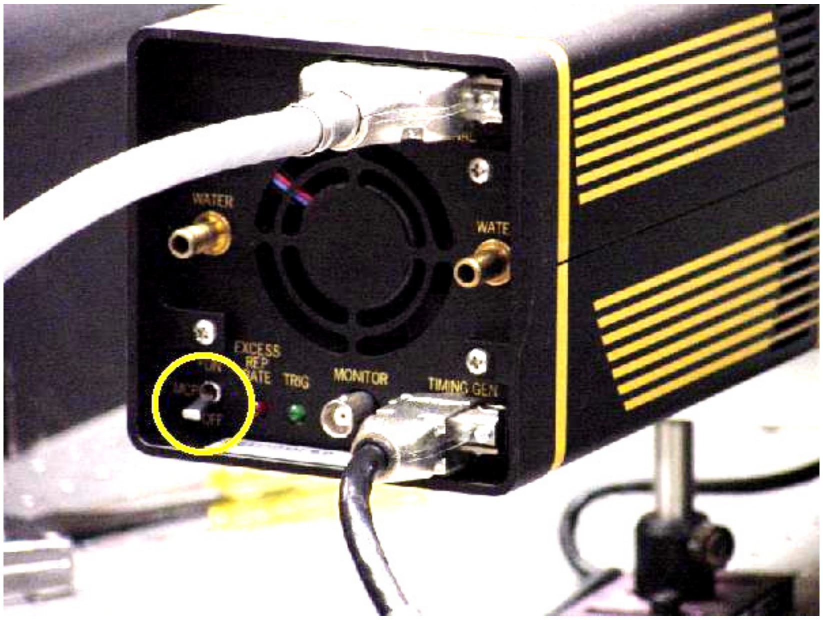


Figure 16. Picture of the CCD. The yellow circle highlights the location of the “OFF/ON” switch. Currently the camera is in the “OFF” position.

- **Turn on PTG-Pulser located underneath the table. (See Figure 17)**

Figure 17: Picture of the pulser. The yellow circle indicates where the ON/OFF switch is located on the pulser. Currently, the Pulser is in the OFF position

NOTE: Throughout this manual, the word “camera” and CCD are used interchangeably.

WinSpec

- **Open WinSpec, located at Start → Program Files → Roper Scientific → WinSpec32.**
- **After approximately 15 seconds, the following window should appear. (Figure 17)**

Figure 18: Menu seen upon opening WinSpec.

  - If not, exit WinSpec, turn off the ST-133 Controller and turn it on again. Open WinSpec again. If this fails, it is recommended to turn off all CCD related material (CCD, transformer, and pulser) and reboot the computer.

- **Select the appropriate camera state**

  There are 3 options for the camera state:

  a. Keep in Safe Mode
  b. Restore to Last Settings
  c. Restore Defaults

  When in doubt, keep the camera in Safe Mode. This turns off the CCD and prevents any strong light from damaging the CCD. Restore to Last Settings is used if the settings (calibration, accumulations, gain, exposures, etc.) are identical to before.

- **Before any optimization can begin, the fluorescence spectrum must be centered. This can be done by going to Spectrograph → Move… (See Figure 19)**

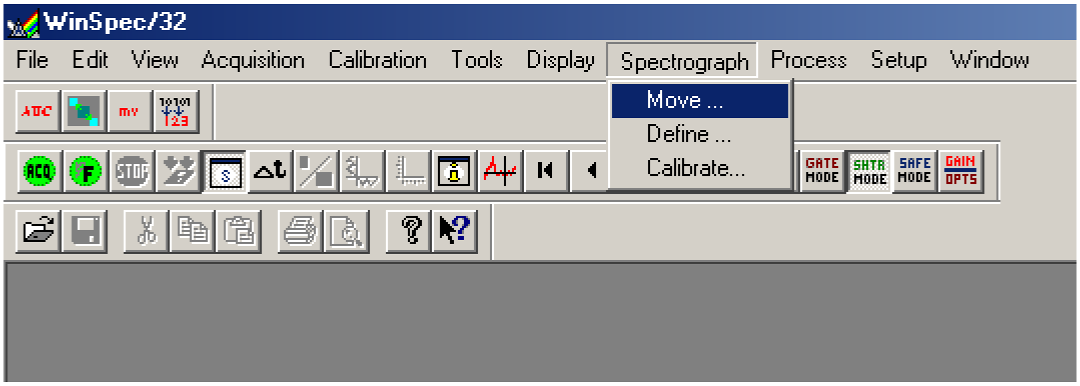


Figure 19: Location of moving the grating to center fluorescence spectrum.

- **The following screen should appear. Select the appropriate grating the center wavelength.**

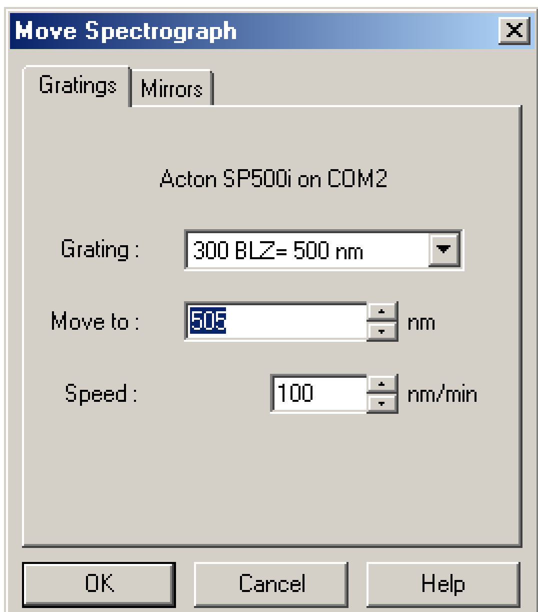


Figure 20: Picture of the Move Spectrograph

Grating tells you how large the window is.

300 BLZ = 90 nm on either side of the center (Total window length is 180 nm)

600 BLZ = 44 nm on either side of the center (Total window length is 88 nm)

1200 BLZ = 20 nm on either side of the center (Total window length is 40 nm)

Setups

WinSpec offers flexibility when determining the quality of the data collection. Two of the most used setups menus are “Experimental Setup” and “Pulser…” setup.

Experimental Setup

Experimental Setup is located under Acquisitions → Experimental setup (see Figure 21) Experimental Setup dictates how the computer collects data from the CCD. (See Figure 22) This differs from Pulser Setup, which is responsible for how the CCD collects the data. (See Figure 24) Specifically, the Pulser Setup controls the timing issues

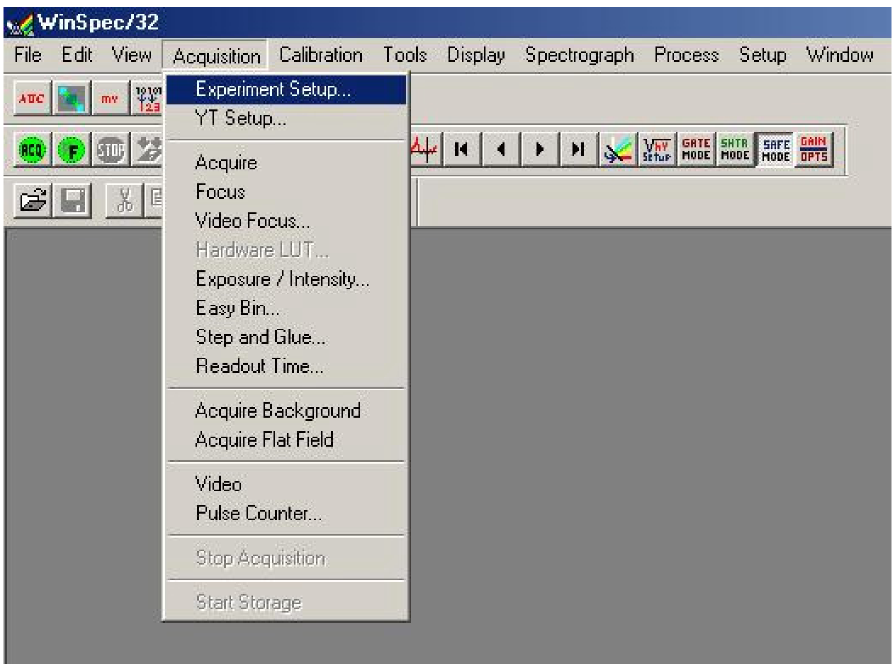


Figure 21: Location of Experimental Setup, the menu to access Accumulations, Gain and number of spectra.

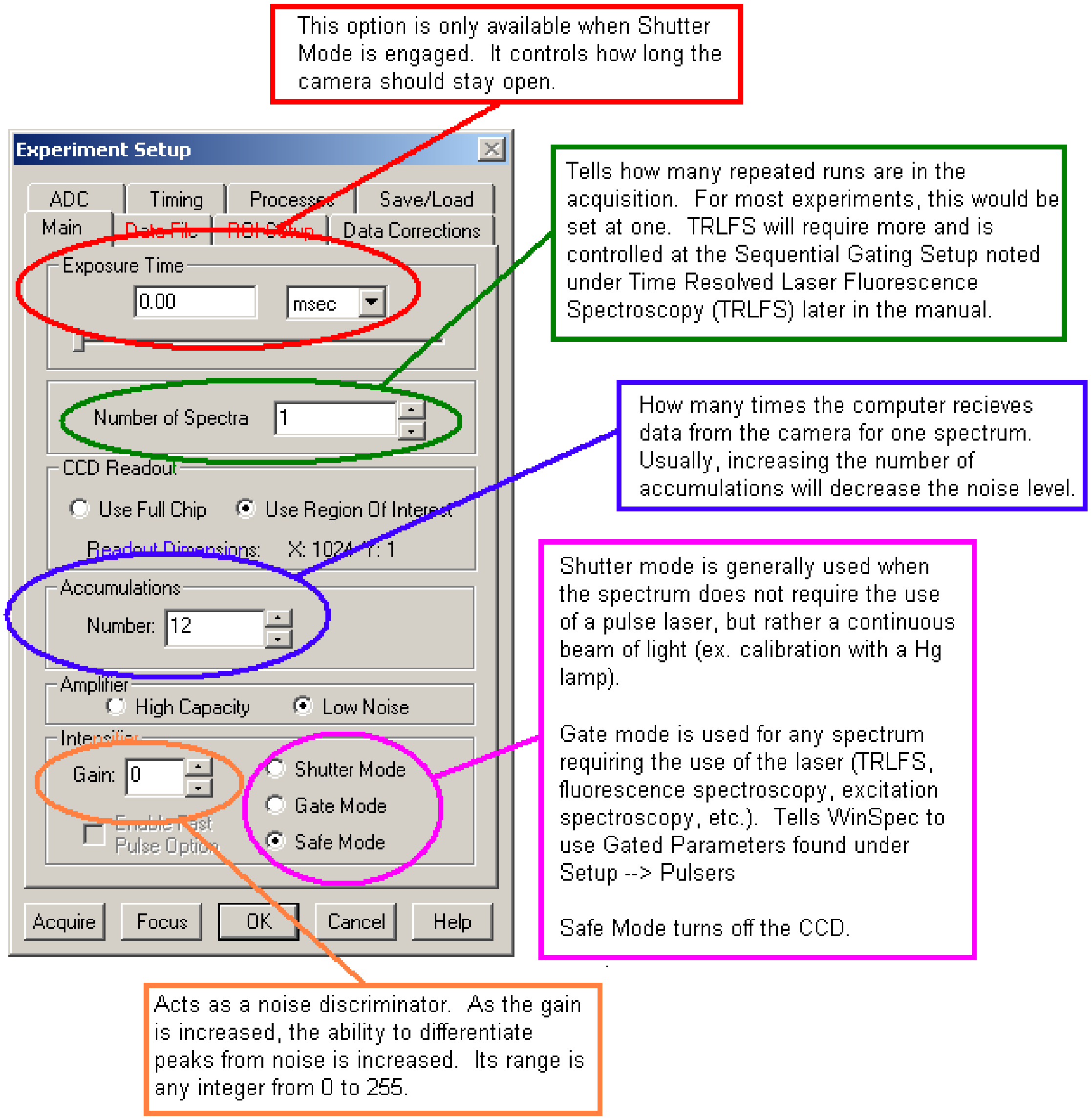


Figure 22: Experimental Setup Menu.

Pulser Setup (Repetitive Mode)

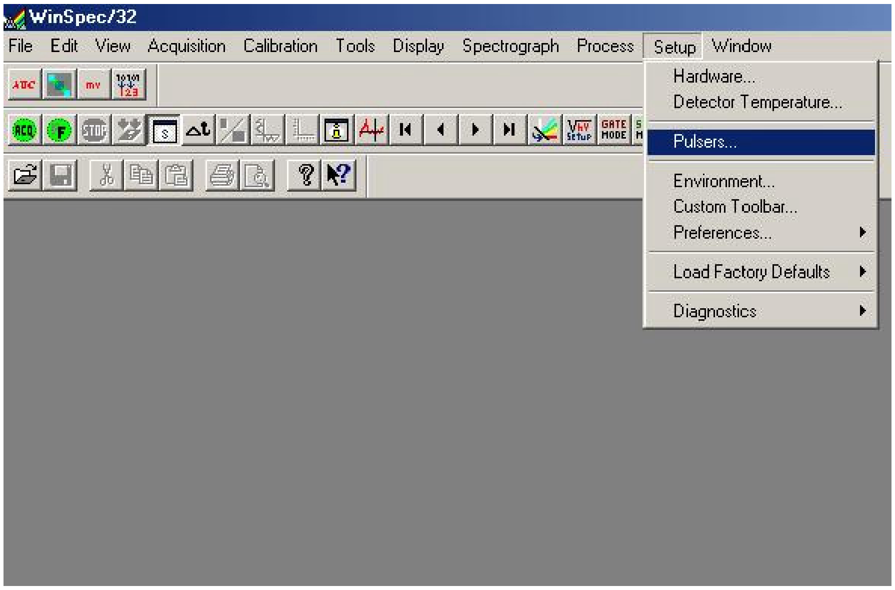


Figure 23: Location of Pulser Setup,

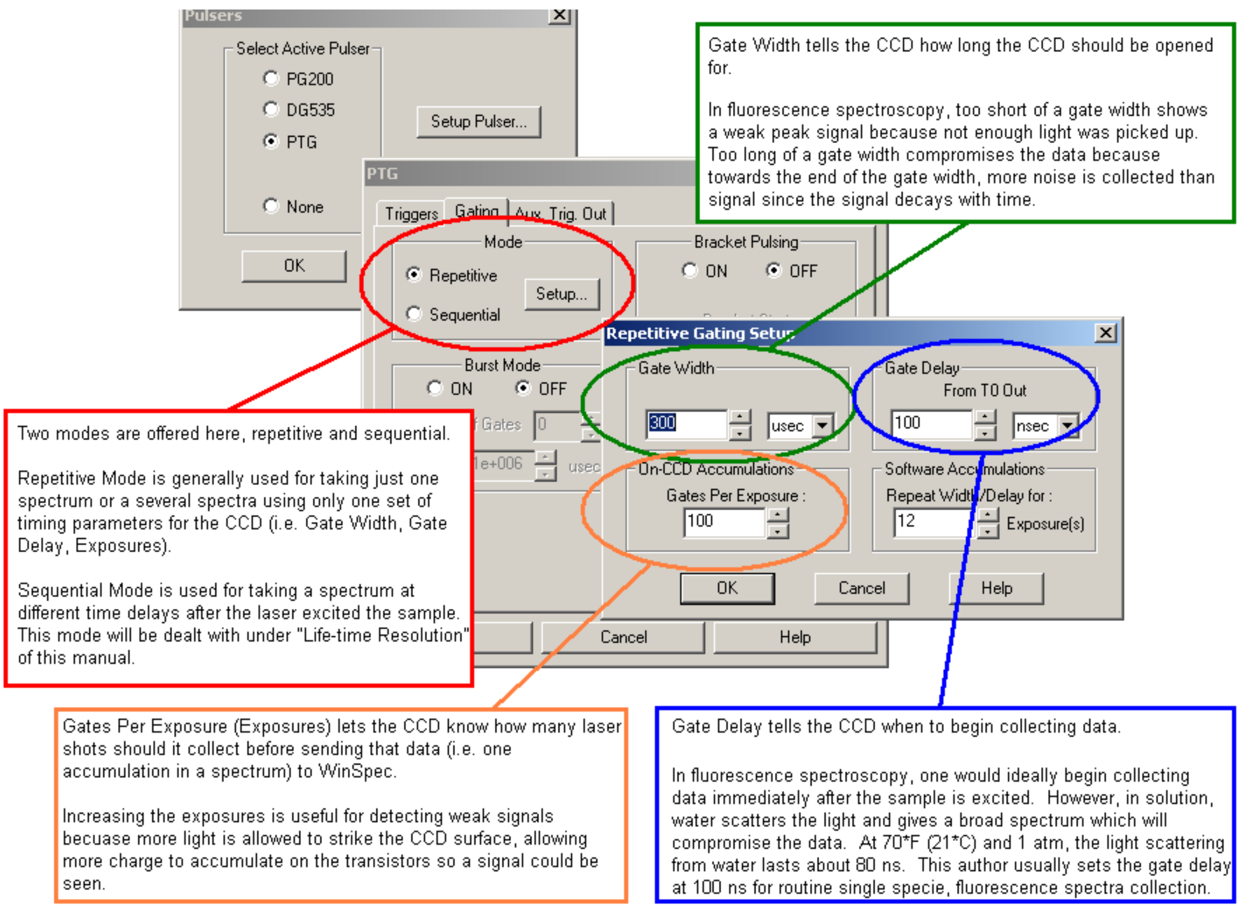


Figure 24: Picture of Pulser setup in Repetitive Mode.

Useful Hardware Tips for Data Optimization

Since the laser beam has a finite width, it is best to have the at least 1.5 mL of solution in a 1 cm pathlength cell. Anything less than 1.5 mL has a probability that the full potential of the fluorescence signal is not exhibited.

The slit is used to control the amount of light entering the monochrometer and an attempt to make the light a point source. Closing the slit increases the resolution (how detailed/precise the spectrum is) but dramatically weakens the signal and increases the noise. Opening the slit causes the peak width to increase and is used for a more accurate quantitative measurement (ex. complexation constants or concentration measurements).

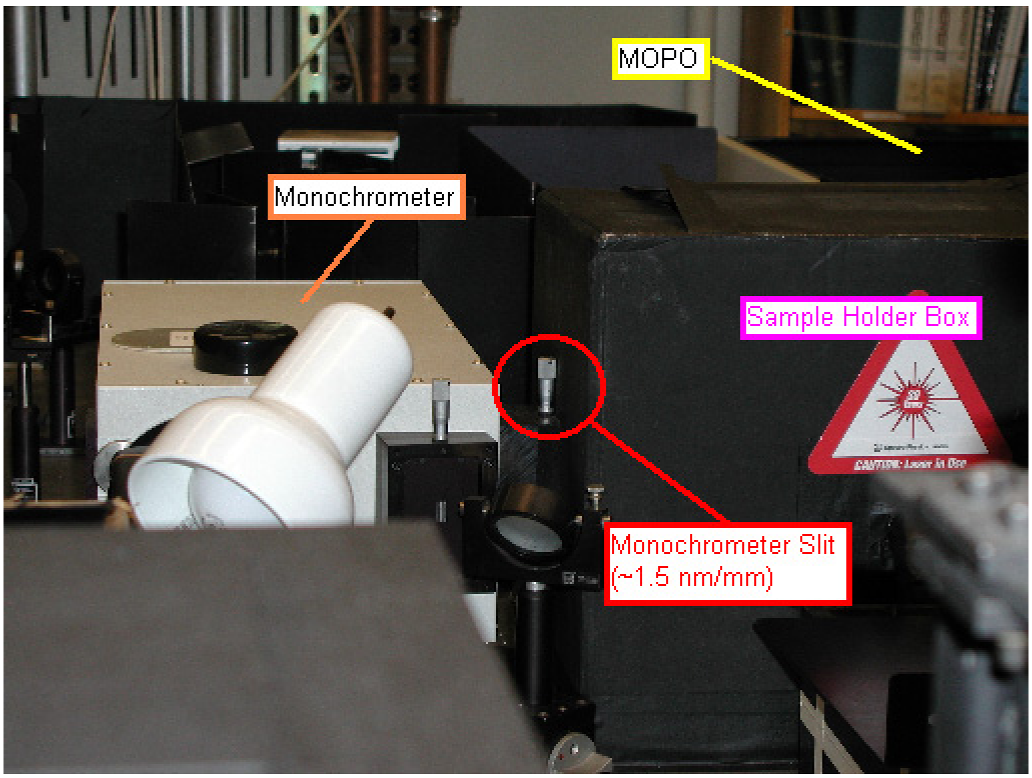


Figure 25: location of knob controlling the monochrometer.

The slit can be adjusted by a knob found between the black sample box and the monochrometer (see Figure 25). Each clockwise revolution of the knob represents 250 μm increase in slit width. According to the manuals, the dispersion is ~1.7 nm. mm^{-1}.

The above suggestions are not hard-and-fast rules, but are a good "rule-of-thumb" estimate. It is best to take spectrums at different slit width, accumulation, exposures, gains, and concentrations to optimize spectrum parameters.

Pulser Setup (Sequential Mode)

One unique characteristic found within species that fluoresce are their lifetimes. WinSpec offers an automated lifetime collection which may be found under Setup → Pulsers → Setup Pulsers. Under the "Gating" tab, select the "Sequential" mode, and click setup. Below is the WinSpec Sequential Gating Setup box with a short description what the most commonly used features are.

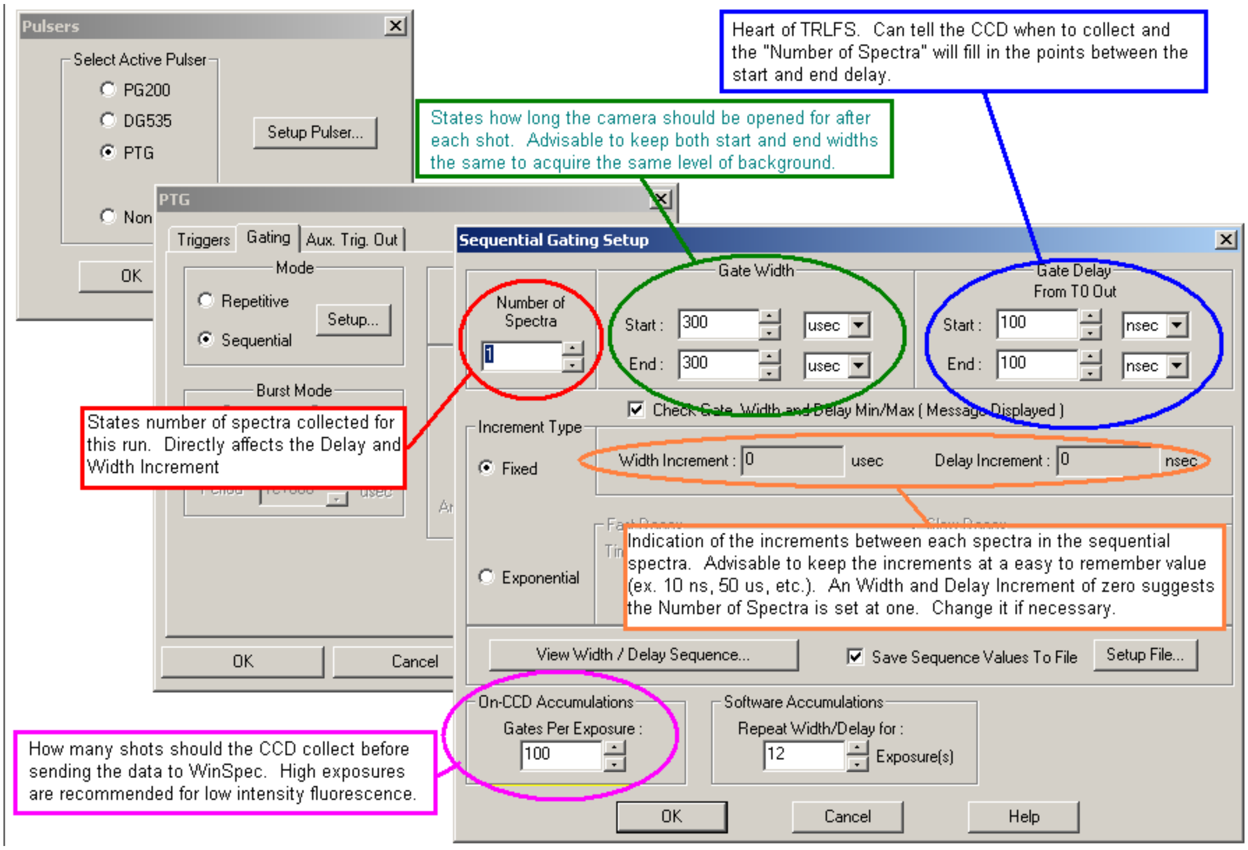


Figure 26: Picture of Pulser setup in Sequential Mode, generally used for TRLFS.

Note: Be sure to reset the Number of Spectra in the Experimental Section (see Fig. 22) to one (1) if you revert from TRLFS to a fluorescence spectrum. (Ex. If you do a TRLFS for 24 spectra (which you typed 24 in the "Number of Spectra" in the Sequential Gating Setup (see Figure 26), then decide to do a single fluorescence spectrum, be sure to reset the "Number of Spectra" in the "Experimental Setup" back to one (see Figure 22). Otherwise, when acquiring for the single fluorescence spectrum, you will be running it for 24 spectra instead of one.)

Calibration

Depending on the spectrum range, different calibration lamp should be use. Refer to the WinSpec manual offers an excellent treatise in calibration.

Shut down:

1. **Press "RUN LP" (hold until beeps) in menu, wait 5-10 min. This is critical for the crystals.**
2. **Press "Q-SWITCH OFF", press "LAMP OFF" wait 10-15 min until cooling water output is cold.**
3. **Press "POWER OFF".**
4. **Switch off Nd-YAG and MOPO controller (backside).**
5. **Turn key on laser power supply to off. Leave switch below key always on, to heat the crystals!!!**
6. **Turn off water and interlock.**
7. **Let the Nitrogen purge continue for 24 hours before turning off.**

Note: Essentially, this is the reverse of the Start Up procedure described in the beginning of the manual.

Never block the Nd YAG laser beam manually (with shutter, paper). When beam hit crystals in MOPO without warm up procedure crystals can be damaged !!!!! Always press "RUN LP" to shut off laser beam and press " RUN NORM" to start beam.

Appendix 1: Glossary

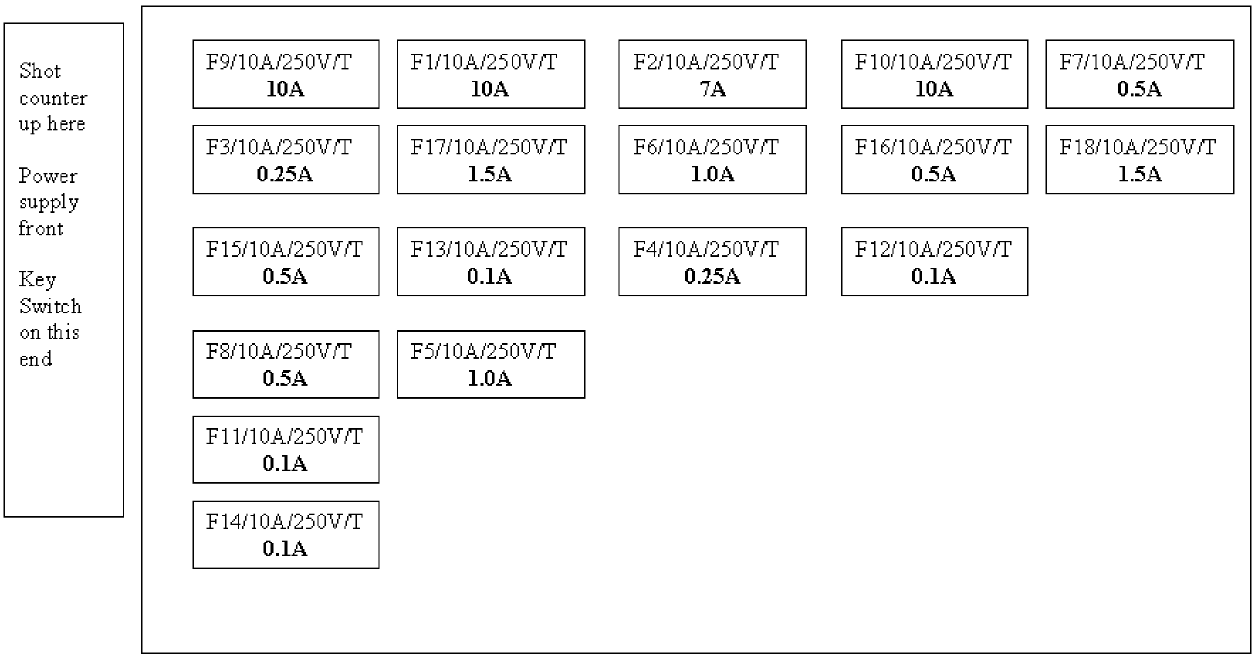
Accumulations	How many times the computer receives data from the CCD for one spectrum. Generally, increasing the accumulations gives a smoother spectrum. (Pg. 17,18)
BBO	Beta Barium Borate. A nonlinear crystal where by changing the angle, the the resulting wavelengths change.
Camera	See CCD
Charged Coupling Device (CCD)	Used interchangeably with camera in this manual. A device which accumulates charge on its surface proportional to the amount of light striking it. Excellent for high quality, low noise spectra.
Dispersion	Measures ability of monochrometer of resolving two peaks.
Exposures	Lets the CCD know how many laser shots should be collected before sending the data to the computer as one accumulation. (Pg. 19)
FDO	Frequency Doubling Option. Allows the MOPO to operate in the 220-440 nm region. It literally doubles the Nd-YAG frequency from 534 nm to 267 nm. (Pg. 1, 8-12)
Flashlamps	In a laser, the lamp which flashes to excite the lasing medium.
Fluorescence	Type of luminescence. In excited singlet states, the electron in the excited orbital has the opposite spin of the second electron in the ground state orbital, which is a spin-allowed transition and the emission rate is fast (<1 microsecond).
Gain	Acts as a noise discriminator.
Gate Delay	Tells the CCD when to begin collecting after a laser shot has passed through the sample. (Pg. 19, 21)
Gate Width	How long should the camera be opened for each shot. (Pg. 19, 21)
Gates Per Exposures	See Exposures
Gratings	Number of diffraction lines per
Half life	Time it takes for a fluorescence to decay to half of its intensity
Idler Wavelength	See Signal Wavelength.
Interlock	Fail-safe pieces of hardware designed to disable the Nd-YAG system should any of the pieces be defeated. Two general types of interlock, those to protect against intruders (ex. door interlock) and those to protect the equipment (ex. cooling water interlock)
Lifetime	Average time it takes for a fluorescence to decay to its ground state
Luminescence	Emission of light from any substance that occurs when an electron in the excited state relaxes to the ground state. See phosphorescence and fluorescence.
Monochrometer	Device used to diffract light and select a small portion of the wavelengths.
MOPO	Master Oscillator Power Oscillator.
Nd-YAG	Neodymium - Yttrium Aluminum Garnet.
Non-Radiative Transitions	A path for an electronically excited atom or molecule takes to return to the ground state without emitting a photon.
Phosphorescence	Type of luminescence. In excited triplet states, the electron in the excited orbital has the same spin as the second electron in the ground state orbital. This is a forbidden transition, so the emission rate is slow (>1 millisecond).
PTG	Programmable Timing Generator. See pulser
Pulse	An arbitrary unit of measurement of the laser's power. Pulse can be adjusted by two knobs on the Nd-YAG (Pg. 7) and be affected by warm up time, age of flashlamps, and temperature. (Pg. 6, 7)
Pulser	Used interchangeably with PTG. A device used to control timing parameters of the CCD. (Pg. 14, 19)
Quenching	A decrease in fluorescence intensity. Wide array of process that causes quenching. Example: when target molecule/element binds with a nonfluorescent compound, when the excited target molecule/element is deactivated from colliding with another compound.
Radiative Transitions	A path for an electronically excited atom or molecule takes to return to the ground state by emitting a photon.
Resolution	The degree one is able to differentiate two peaks. See Dispersion.
scfh	Standard cubic feet per hour. Measurement of flow rate at 1 atmosphere pressure and 25ºC.
Shots	Number of times the laser has fired.

Signal Wavelength	After the Nd-YAG beam passes through the BBO, two beams of different wavelengths are seen. The beam with the longer wavelength is the Idler Wavelength and the beam with the shorter wavelength is the Signal Wavelength. The summation of the energy of the two beams equals the energy of the Nd-YAG.
Simmer	Refers to the flashlamps being in a charged, but idle state.
Slit Width	How wide the slit is on the monochrometer. The smaller the slit, the better peaks can be resolved, but the nosier the spectrum gets. (Pg. 20)
Spectrum	A representation (usually graphical) of characteristics
TRLFS	Time Resolved Laser Fluorescence Spectroscopy. Technique used to determine number of species present by discovering how many different lifetimes are present.

Appendix 2: Laser Power Supply Fuse Positions

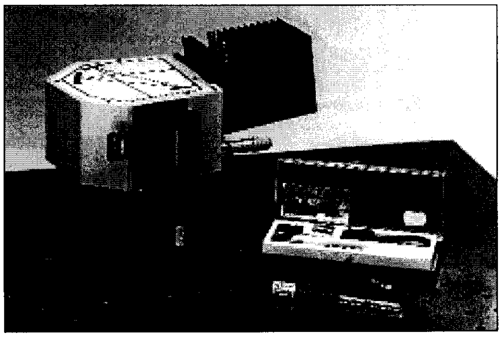
Note just the board for the location of the fuses is shown, no other laser components are diagramed

The values in bold represent the Ampere value of the fuse in the location



Appendix 3: Spectral Calibration Lines for Selected Lamps

ORIEL INSTRUMENTS **PENCIL STYLE SPECTRAL CALIBRATION LAMPS** PAGE 1 of 5



Spectral Calibration Lamp mounted to MS125™ Spectrograph, using the 77251 Lamp Mount. A diode array detector is on the output of the MS125™.

- **Compact and simple tools for calibrating spectral instruments**
- **Narrow, discrete UV to IR wavelengths**
- **Excellent stability**
- **Supported by mounting and fiber optic accessories for efficient coupling**

These "Pencil Style" mercury and rare gas sources are used for wavelength calibration of spectroscopic instruments such as monochromators, spectrographs, and spectral radiometers. They produce narrow, intense lines from the excitation of various rare gases and metal vapors. We also offer a full range of accessories, from mounts and holders to fiber optic adapters and aperture shields.

WHICH LAMP DO I CHOOSE?

We offer six lamps; choose the lamp or lamps which suit your wavelength range, using Table 1 as a guide. The single gas lamps (Xe, Ar, Ne and Kr) have distinct lines; the Hg(Ar) and He(Ne) share the mercury lines, but also have distinct differences:

Mercury (Argon) Lamp

- Preferred lamp for calibration, using mercury line spectrum
- Temperature insensitive
- Average intensity is constant and reproducible
- Longer life
- Prefered lamp for calibration using Mercury line spectrum

The 6035 Hg(Ar) lamp is insensitive to temperature. It requires a two minute warm-up for the mercury vapor to dominate the discharge, then 30 minutes for complete stabilization. The average intensity is remarkably constant and reproducible after the thermal conditions stabilize.

Mercury (Neon) Lamp

- Emits additional lines in the VIS-NIR
- Temperature dependent

The 6034 Hg(Ne) Lamp is temperature dependent. When run in normal lab ambient, the output is very similar to that of the Hg(Ar) lamp, that is the characteristic mercury line spectrum. Forced air cooling (i.e. from a muffin fan) of the lamp adds the neon lines to the output. This spectrum has a large number of useful calibration lines in the longer VIS and NIR regions; see Table 1.

Table 1 Usable Wavelengths of Spectral Calibration Lamps

Lamp Type (Model No.)					
Hg(Ar) (6035)	Hg(Ne) (6034)	Xenon (6033)	Argon (6030)	Neon (6032)	Krypton (6031)
Wavelength (nm)					
184.9	253.65	418.0	294.3	585.25	427.4
187.1	296.73	419.3	415.9	594.48	432.0
194.2	302.15	433.1	420.1	607.43	435.5
253.65	312.57	439.6	427.7	609.62	457.7
265.4	313.15[1]	444.8	476.5	614.31	461.9
284.8	313.18[1]	446.2	488.0	616.36	465.9
302.2	365.02	473.4	696.54	621.73	473.9
312.57[1]	404.66	480.7	738.40	626.65	476.6
313.15[1]	435.84	483.0	750.39	630.48	483.2
313.18[1]	546.07	508.1	751.47	633.44	557.0
320.8	576.96	529.2	763.51	638.30	587.1
326.4	579.07	531.4	772.38[1]	640.11[1]	758.74
345.2	614.31*	554.0	772.42[1]	640.22[1]	760.15
365.02	638.30*	541.9	794.82	650.65	769.45
404.66	640.11[1]*	547.2	801.48	653.29	769.45
435.84	640.22[1]*	597.7	811.53	659.90[1]	785.48
546.07	650.65*	603.6	826.45	660.29[1]	805.95
576.96	703.24*	605.1	840.82	667.83	810.44
579.07	1013.98	609.8	842.46	671.70	811.29
615.0	1128.74	659.5	912.3	692.95	819.00
1014.0	1357.02**	680.5	922.4	703.24	826.32
1357.0	1367.35**	699.1	965.8	717.39	829.81
1692.0	1529.58	823.2	1047.1	724.52	829.81
1707.3	1688.15**	828.0	1331.3	743.89	850.9
1711.0	1692.02**	834.7	1336.7	783.9	877.7
	1694.20**	840.9	1371.8	792.7	829.9
	1707.28**	881.9	1694.0	793.7	975.2
	1710.99**	895.2		794.3	1363.4
	1732.94**	980.0		808.2	1442.7
	1813.04**	992.3		811.9	1523.9
	1970.02**	1262.3		812.9	1533.4
		1365.7		813.6	1678.51
		1473.3		825.9	1689.04
		1541.8		826.6	1689.68
		1672.8		826.7	1693.58
		1732.5		830.0	1816.73
		2026.2		836.6	
		2482.4		837.8	
		2626.9		841.7	
		2651.0		841.8	
				846.3	
				848.8	
				849.9	
				854.5	
				857.1	
				859.1	
				863.5	
				864.7	
				865.4	
				865.6	
				867.9	
				868.2	
				870.4	
				877.2	
				878.0	
				873.4	
				885.4	
				920.7	
				930.1	
				932.7	
				942.5	
				948.7	
				953.4	
				1056.2	
				1079.8	
				1084.5	
				1114.3	

[1] **Adjacent lines will remain unresolved on many spectroscopic systems.**

* **These are neon lines brought out by forced air cooling.**

** **These lines are very weak, but forced air cooling makes them more useful.**

Above: Calibration lines for pen lamps obtained from http://www.oriel.com/netcat/VolumeIII/pdfs/v39pen.pdf .

Table 2. Recommended Wavelengths (Air) and Wave Numbers (Vacuum) for Selected Hg Spectral Lines Emitted by Pencil-Type Lamps

Intensity[a]	Wavelength[b] (nm)	Wave Number (cm^{-1})
300,000	253.6521	39412.236
160	289.3601	34548.888
2600	296.7283	33691.025
280	302.1504	33086.464
2800	312.5674	31983.828
1900	313.1555	31923.765
2800	313.1844	31920.819
160	334.1484	29918.220
5300	365.0158	27388.271
970	365.4842	27353.171
110	366.2887	27293.096
650	366.3284	27290.138
4400	404.6565	24705.339
270	407.7837	24515.883
34	434.7506[b]	22995.229
10,000	435.8335	22938.095
10,000	546.0750	18307.415
1100	576.9610	17327.389
1200	579.0670	17264.372

[a]Intensities are relative values based on irradiance values from Ref. 1 with the intensity of 436 nm set arbitrarily to 10,000.
[b]The wavelength uncertainty is 0.0001 nm, with the exception of that of the 434.7506-nm line (see text).

5. Discussion

Precise wavelength measurements for natural Hg have previously been reported by Burns *et al.*[7] Comparison of our results with the earlier values shows significant deviations. All lines from the pencil lamps are shifted to the red by an average of 0.00068(32) nm with respect to the Fabry-Perot measurements by Burns *et al.*[7] It is not clear whether this shift represents a real difference between the pencil lamps and the positive column source used in Ref. 7 or whether it is a result of measurement of weakly exposed, partially resolved line profiles by Burns *et al.*[7]

We have also compared the pencil-lamp results with our measurements of the Hg lines in the natural-Hg electrodeless discharge lamp. For this

Table 3. Comparison of 198Hg Wavelengths Derived from Our High-Resolution Fourier-Transform Spectrum of a Natural-Mg Electrodeless Lamp with the Results Obtained by Kaufman[a]

Vacuum Wavelength (nm) This Study[b]	Kaufman[c]	Deviation (nm)
546.227060	546.227063	-0.000003
407.898902	407.898940	-0.000038
404.771464	404.771469	-0.000005
435.975227	435.975257	-0.000030

[a]Ref. 4.
[b]Derived from the fully resolved, hyperfine-structure components of ^{199}Hg by use of intervals measured by Blaise and Chantrel.[6]
[c]Calculated from the optimized energy levels for ^{198}Hg in a lamp with a pressure of 400 Pa (3 Torr) Ar.[4]

comparison the high-resolution spectrum of the electrodeless lamp was degraded to a resolution of 1.0 cm-1 by convolution with a Gaussian as was done for the pencil lamps. Again the pencil-lamp wavelengths were found to be consistently shifted to the red, in this case by an average of 0.00054(25) nm. On the basis of the pressure shifts measured by Kaufman,[4] a shift of this size is too large to be explained by the Ar pressure in the pencil lamps. The shift may be attributable to a higher pressure of Hg in the pencil lamps, which operate at a significantly higher temperature than the electrodeless lamp. In any event, our present results represent the Hg wavelengths as emitted by the pencil lamps and should not be applied to other types of low pressure Hg lamps if an accuracy higher than 0.001 nm is required.

We note that wavelengths emitted by the pencil lamps at different discharge currents or with ac excitation may differ slightly from those obtained in this work. We thus recommend that, if these lamps are used in applications for which accuracies of better than 0.0005 nm are required, our experimental conditions should be carefully reproduced.

6. Conclusion

In summary, we have made precise measurements of the Hg lines emitted from three Hg-Ar pencil lamps. With the exception of the 434.7-nm line, the wavelengths are consistent for the three lamps observed, and the values we present should be useful as wavelength standards at the level of 0.0001 nm for instruments with resolving powers of less than 17 000.

We thank Bruce Pulliam for making available his spectrum-measuring and spectrum-analysis software, for modifying it to better meet the needs of our ongoing Hg observations, and for coming to the National Institute of Standards and Technology to install and test it on our computers.

References and Notes

1. J. Reader, C. J. Sansonetti, and J. M. Bridges, "Irradiances of spectral lines in mercury pencil lamps," Appl. Opt. 35, 78-83. (1996).
2. Certain commercial products are identified in this paper to specify adequately the experimental procedure. Such identification does not imply a recommendation or endorsement by the National Institute of Standards and Technology.
3. A. R Thorne, C. J. Harris, I. Wynne-Jones, R. C. M. Lerner, and G. Cox, "A Fourier transform spectrometer for the vacuum ultraviolet: design and performance," J. Phys. E 20, 54-60 (1987).
4. V. Kaufman, "Wavelengths, energy levels, and pressure shifts in mercury-198,"J. Opt. Soc. Am. 52, 866-870 (1962).
5. R. C. M. Learner and A. R Thorne, "Wavelength calibration of Fourier-transform emission spectra with applications to Fe I," J. Opt. Soc. Am. B 5, 2045-2059 (1988).
6. J. Blaise and H. Chantrel, "Structures hyperfines de raies du spectre d'arc du mercure et moment quadrupolaire de ^{201}Hg,"J. Phys. Radium 18, 193-200 (1957).
7. K. Burns, K. B.Adams, and J. Longwell, "Interference measurements in the spectra of neon and natural mercury,"J. Opt. Soc. Am. 40, 339-344 (1950).

Above: Calibration lines for Hg mercury lamp obtained from **http://www.uvp.com/pdf/wavelengths.pdf**

Appendix 4: Getting Started Cheat Sheet

Getting Started

Before turning on the laser be sure to remove any metallic or reflective jewelry including watches, rings, and necklaces, basically anything that could get in the path of the laser and reflect the beam. Please record the number of shots on the flash lamp when you first power up the laser and when you are finished. This should be recorded in the laser lab notebook with the average reading from the power meter, the laser pulse, and the maximum power (the units are arbitrary). Please remember to clean up after your self, this includes appropriately taking care of any waste generated, cleaning out cuvettes, and removing all scratch and other unnecessary papers. Ideally leave the lab cleaner than when you came in, remembering however that this is a shared space and ask before removing or altering an item.

Laser Lab Reminders Setup

1) Turn on door interlock system
2) Check that N_2 gas valve is on
3) Turn water valve to a 45° angle
4) Check that gas is flowing (0.4-0.6 scfh)
5) Make sure that water is present in the reservoir on the side of the power supply is between the two level markers during operation.
6) Turn on laser key
7) Turn on MOPO and Nd-YAG box.
8) Press the Nd-YAG "POWER ON" in the front. **LET THEM WARM UP FOR 10-15 minutes!**
9) Press "RUN LP" and **LET IT WARM UP FOR 20-30 min!**
10) Press "RUN NORMAL"
11) Adjust the crystal in the laser system (Pulse maximum will be somewhere near 880-1000. Wear laser goggles at 534 nm)
12) **LET Nd-YAG WARM UP FOR 30 min!**
13) On the MOPO controller under "SETUP 1" enter the BEGIN and END wavelength that will bracket the target wavelength (ex. if the target wavelength is 410 nm an appropriate start and end points are 380 and 420 nm respectively).
14) Under "OPERATE 1" enter the desired GOTO point.
15) Under "SETUP 2", choose the appropriate crystal to change. (look at chart in the FDO manual to determine which device is appropriate under the target wavelength) press and hold. Then press and hold "METHOD MANUAL". Change the up and down button to maximize the power (13,000-14,000)

Reminders

When using the laser be sure to save your data and write down all information pertaining to the laser itself and the parameters set for that run including

1) Slit width
2) # of accumulations
3) gain
4) delay
5) exposure
6) width
7) center wavelength of spectrum and the grating number (in BLZ)

Also be sure to write down what the file name is, there are a lot of files on the computer and it makes data analysis simpler.

The Nd-YAG laser operates at 1068 and 534nm.

Pulse operation	10Hz
Pulse duration	12ns
Beam energy	3 mJ/cm^2
Beam power (upon deliverance)	300,000 kW
Average power	30mW
Beam diameter	~1cm
Beam divergence	< 1mrad
Resolution	~1.5nm/mm

References:

Oriel Instruments. "Pencil Style Spectral Calibration Lamps". Oriel Instruments, part of Spectra-Physics. **http://www.oriel.com/netcat/VolumeIII/pdfs/v39pen.pdf**

Roper Scientific. *WinSpec Princeton Instruments Spectroscopic Software, User Manual, Version 2.5A*. Roper Scientific. January 5, 2001

Roper Scientific. *PTG Programmable Timing Generator; Operation Manual, User Manual, Version 1, Revision C.* Roper Scientific. October 27, 1999

Sansonetti, Salit, Reader. "Wavelengths of spectral lines in mercury pencil lamp". Applied Optics, January 1996. **http://www.uvp.com/pdf/wavelengths.pdf**

Spectra-Physics. *Quanta-Ray MOPO-SL, Optical Parametric Oscillator, User's Manual.* Spectra-Physics. Part Number 0000-263A, Revision C. February 2000

Spectra-Physics. *FDO-900, Frequency Doubler Option, User's Manual.* Spectra-Physics. Part Number 0000-244A. January 1996

Spectra-Physics. *Quanta-Ray Pro Serier, Pulsed Nd:YAG Lasers, User's Manual.* Spectra-Physics. Part Number 0000-257A, Revision A. January 1999.

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